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DEVELOP AND TEST FUEL CELL POWERED ON-SITE INTEGRATED TOTAL ENERGY SYSTEMS: PHASE III, FULL-SCALE POWER PLANT DEVELOPMENT

7TH QUARTERLY REPORT: AUGUST - OCTOBER, 1982

ENGELHARD INDUSTRIES DIVISION
ENGELHARD CORPORATION
EDISON, NJ 08818
A. Kaufman, Contract Manager
G. K. Johnson, Contract Technical Coordinator

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SECTION I. INTRODUCTION

Engelhard's objective under the present contract is to contribute substantially to the national fuel conservation program by developing a commercially viable and cost-effective phosphoric acid fuel cell powered on-site integrated energy system (OS/IES). The fuel cell offers energy efficiencies in the neighborhood of 40% of the lower heating value of available fuels in the form of electrical energy. By utilizing the thermal energy generated for heating, ventilating and air-conditioning (HVAC), a fuel cell OS/IES could provide total energy efficiencies in the neighborhood of 80%. Also, the Engelhard fuel cell OS/IES which is the objective of the present program offers the important incentive of replacing imported oil with domestically produced fuel.

Engelhard has successfully completed the first two phases of a five-phase program. The next three phases entail an integration of the fuel cell system into a total energy system for multi-family residential and commercial buildings. The mandate of Phase III is to develop a full-scale 50kW breadboard power plant module and to identify a suitable type of application site. Toward this end, an initial objective in Phase III is to complete the integration and testing of the 5kW system whose components were developed during Phase II. Following the test of this sub-scale system, scale-up activities will be implemented as a total effort. Throughout this design and engineering program continuing technology development activity will be maintained to assure that the performance, reliability and cost objectives are attained.

SECTION II. TECHNICAL PROGRESS SUMMARY

TASK I - 5kW POWER SYSTEM DEVELOPMENT

This task is of limited duration and has as its objective the complete integration of 5kW components developed during Phase II. This integrated 5kW system is automated under microprocessor control.

During August the remaining sub-stacks for the rebuild of the 5kW stack were constructed and the entire stack was assembled. The stack was put on initial test. The current-voltage curves and the current-power curves are shown in Figure 1 for two different hydrogen utilizations.

Prior to reinstallation of the stack, the following changes and additions were made to the microprocessor control program in the integrated system:

- The number of steps in methanol/water and air flow rate control as a function of fuel cell current has been increased to 16 to improve the match between fuel supply and stack current levels.

- The methanol/water flow pressure switch was removed from the program. The corresponding input relay on the relay I/O board was changed to an AC output relay to support the cooling fan. The software to drive the fan was added to the program.

- The safety pressure switches sensing software was modified to ignore occasional pressure fluctuations.

SECTION II. - CONTINUED

- The burner support and safety shut-down software was expanded to obtain continuous anode bleed gas burner flame detection.

- The maximum allowable fuel cell voltage was limited by on/off regulation of the fuel cell air supply at a keyboard-selectable set-point.

- The start-up procedure was refined to include a control system. The link includes Prolog's Dual UART 7304 board, cables and associated software. It permits remote data collection and control from another computer.

- A manual-operator on/off routine was added to the control program. It is now possible to override the control algorithm and turn a blower, pump, or any other system component on or off.

- A malfunction storage routine was added to the program. If a malfunction occurs, an identifying code will be written into the storage for future readout.

In early October the rebuilt 5kW stack was installed in the integrated system and the test program was started. Fifty-five hours' integrated operation was accumulated in October with grid connection. The maximum power drawn so far is 5kW at a stack current density of 136 mA/cm^2 (127 A/ft^2). The maximum calculated stack H_2-utilization has been 65% (low due to a valve leak, later corrected).

Two or three modes of unintended shutdown have been observed; the most serious of these appears to be associated with the Abacus inverter, which shows some operating fluctuations in

possible relationship to grid voltage fluctuations; in an unpredictable manner these swings are sometimes wide enough to result in disengagement from the grid load entirely, leading to fuel cell open-circuit. Since the latter voltage exceeds the maximum input accepted by the inverter (58.5 VDC), the system is difficult to restart from this condition.

Because of cascaded fuel flow, the top portion of the stack has seen excessive amounts of CO (enriched by passing through other portions of the stack). This has apparently caused cell-reversal and consequent permanent damage to the topmost cell; the top four-cell sub-stack has therefore been bypassed and the stack will be operated as an 80-cell stack for the balance of the system test. Later repair is planned. The testing program will continue in November.

TASK II - ON-SITE SYSTEM APPLICATION ANALYSIS

The purpose of this task is to develop an application model for on-site integrated energy systems, with some emphasis on a system of 50kW (electrical) modular capability. The model considers fuel availability and costs, building types and sizes, power distribution requirements (electrical and thermal), waste heat utilization potential, types of ownership of the OS/IES, and grid connection vs. stand-alone operation. The work of this task is being carried out under subcontract by Arthur D. Little, Inc. (ADL).

DEMONSTRATION SITE SELECTION CRITERIA

ADL recommends that the purpose of the demonstration be to prove that a fuel cell OS/IES works and achieves the predicted results. Such a demonstration will aid in developing market interest by proving the practicality of the concept, demonstrating predictive nature of the

SECTION II. - CONTINUED

the economic models and suggesting appropriate design changes. Such a demonstration should be conducted in a site that is relatively unbiased but also controllable. An appropriate site will highlight the positive characteristics of the OS/IES and have sufficient safeguards to protect against unforeseen risks. It will be preferable to find a site of a type with high market potential, but this is much less important than achieving a well conducted, positive, clearly unbiased demonstration. Buildings with very peculiar characteristics, unusual load profiles, very rare applications or over-analyzed conditions, such as commercial laundries, should be avoided if possible.

On this basis, ADL proposes for discussion the criteria listed in Table 1, weighted approximately as follows:

Criteria	Weighting (%)
1. Load Profile	35
2. Electric Rate Structure	35
3. Institutional Factors	10
4. Proximity to Engelhard	10
5. Market Potential	5
6. Projected Rate of Return	5

On a preliminary basis, the proposed criteria point towards buildings with high hot water loads located in the New York/New Jersey area.

SECTION II. - CONTINUED

ECONOMIC ANALYSIS

The economic analysis by ADL has four major steps:

1) Estimation of capital cost of the entire HVAC system with and without OS/IES.

2) Determination of energy costs with and without OS/IES.

3) Identification of preferred operating strategies from the building owner's standpoint.

4) Calculation of owner's rate of return for OS/IES.

The building types included as candidates are hospitals, office buildings, retail stores and apartment buildings. It has already been concluded that the economic analysis is most sensitive to the electric rate structure applicable to the grid to which the building is connected (i.e., the cost of the purchased electricity which is being displaced).

The electric rate structures used for analysis are:

Houston Power and Light (high growth; high oil: gas)
Consolidated Edison (low growth; high oil: gas)
Georgia Power (high growth; low oil: gas)
Commonwealth Edison (low growth; low oil: gas)

Examples of these differences in rates, for a hospital using 3.85 million kWh per year, for example, are:

Con Edison	15.1 ¢/kWh
Georgia	10.5 ¢/kWh
Commonwealth	7.7 ¢/kWh
Houston	5.2 ¢/kWh

SECTION II. - CONTINUED

Some of the bases of the analysis are as follows:

- Analysis starts in 1985.
- Installed cost of the fuel cell system is $2142/kW (1985).
- Inflation rate is 6% per year.
- Cash flows are computed for 25 years.
- Operation of the fuel cell system satisfies cogeneration requirements of PURPA.
- Sizes and types of equipment are optimized for IRR to the owner.
- IRR is calculated after tax of 45%.

Some preliminary data on internal rates of return for the four building types mentioned are given in Table II. Floor areas and type of air-conditioning equipment are listed. In some cases, thermal storage was used. In most cases, only the IRR for the first installed 50kW fuel cell module was calculated. The hospital in Table II is taxed, but non-profit hospitals will be included in later stages of the analysis.

The sensitivity to electric rates under the same conditions is shown in Table III in preliminary fashion. Other senstivities in early stages of examination include:

- weather/climate (insensitive)
- cost/COP of absorption chiller (fairly insensitive)
- installaed cost of fuel cell system (sensitive)

ADL was asked to provide incremental rates of return estimated for modular units beyond the initial module. Table IV gives a preliminary version of these results. A more realistic treatment of thermal storage for the hospital was also included.

SECTION II. - CONTINUED

ADL will continue to refine their results during the next quarter. They will use the results to develop estimates of market penetration into suitably economic building types and locations using projected rates of new construction.

Under separate funding in Task III, The Trane Company is doing engineering and economic studies to define the best approach to HVAC waste heat utilization. In both the ADL work and the Trane work, the hospital, even if taxed, is emerging as the building type giving the best internal rate of return to its owner.

The highest installed cost assumed in the Trane study amounts to $(1985)1500/kW, compared with $2142(1985) used by ADL. With this difference in mind, the comparative IRR data for a 300 kW system installed in a hospital connected to the Con Ed grid are;

ADL	~28%
Trane	~40%

Not all of the other assumptions and conditions in the two studies are equivalent, but the above comparison gives a rough estimate of the prospects in the most likely range of installed costs.

Further details of the sensitivity to installed cost from both studies will be given at a later time.

TASK III - ON-SITE SYSTEM DEVELOPMENT

This task forms the core of the Phase III Contract. Work under this task will result in the breadboard design of a system for an on-site application. The power plant will be designed for a rated output of 50kW (electrical) or some multiple thereof. The fuel

processor and power conditioner will each be 50kW modules, while the 50kW fuel cell will comprise two 25kW stack modules. This task is accordingly broken down into four sub-tasks as follows:

3.1 Large Stack Development (97048)
3.2 Large Fuel Processor Development (97038)
3.3 Overall System Analysis (97051)
3.4 Overall System Design and Development (97064)

A large part of Sub-Task 3.3 is being carried out by Physical Sciences Inc. (PSI) under subcontract.

LARGE STACK DEVELOPMENT

The furnace modifications for continuous CVD procesing of needled-felt for distribution plates have been completed by Pfizer. Initial static test runs are in progess, and a pilot run on a short roll of felt is planned within a few weeks.

Design drawings and a full-scale mock-up of the 25kW stack have been completed. The design package has been submitted for NASA management approval.

LARGE FUEL PROCESSOR DEVELOPMENT

Two runs were made with the 5kW shell-and-tube reformer loaded with 75% catalyst charge. To lower the temperature of flue gas from the burner, air was injected between the flame and the fuel preheat heat-exchanger coil. In the first test (Figure 2), the process gas temperature at the reformer inlet was 700K. The resultant methanol conversion was 92.3%. In a similar test reported last month, methanol conversion was 99.8% with the entrance temperature at 756K.

SECTION II. - CONTINUED

These results illustrate the strong dependence of methanol conversion on the process gas entrance temperature. (Activation energy about 17 Kcal/mole.)

Entrance temperature is not the only operating parameter influencing methanol conversion. The second test held the entrance temperature constant, but lowered the flue gas mass flow rate by decreasing the burner excess air from 122 to 19%. The resulting methanol conversion (Figure 3) was 86.7%, indicating the importance of heat-transfer characteristics within the reformer.

In all of the tests to date (including tests with inerts), the flue gas temperature was slightly lower than the process gas temperature in the exit half of the reactor. This indicates that all of the heat transfer to the process gas occurs at the front end of the reactor, after which the direction of heat transfer reverses slightly. In the latter case, the flue gas temperature falls below the process gas temperature because of heat loss to the surroundings.

These observations are not unexpected in this case of cocurrent heat transfer between flue and process gases. It is expected that with large equipment (with a diminished degree of heat loss because of lower outside surface per volume of catalyst) there will be essentially a coincidence of process and flue gas temperature curves at the exit end of the reactor.

Design, costing and purchase orders for the 50kW fuel processor have been completed. Burner drawings from the McGill Co. have been approved for construction. The burner is expected in November. The shell-and-tube reformer has arrived from the Perry Co.

OVERALL SYSTEM ANALYSIS

Final reports have been received from PSI on the two principal segments of their subcontract work: system transient

SECTION II. - CONTINUED

analysis and off-design analysis. These will be made available separately to NASA management.

TASK IV - STACK SUPPORT

The purpose of this task, which will continue throughout the contract, is to investigate new materials and component concepts by experimentation and the use of small-stack trials. The criteria for choosing activities under this task will be the possibilities of improved performance or reduced cost, or both. Improvements in and performances of electrocatalysts, though generated under Engelhard-sponsored Task VI, will be reported under Task IV.

A 10-cell 1-ft^2 stack has been assembled for testing non-metallic cooling plates and wet-proofed graphite ABA plates. This stack has been tested for nearly 200 hours as of October 31. No evidence of reactant cross-over has been observed. The open-circuit voltage of 822 mV/cell on H_2/air at 455K (360 °F) is satisfactory. The average IR-free cell voltage at 161 mA/cm^2 (150 A/ft^2) is 686 mV (an acceptable electrode performance). The performance of non-metallic cooling plates is generally satisfactory. Two remediable problems have been identified in the stack: (1) excessive IR-drop averaging 90 mV/cell associated with poor bonding of the ABA bipolar plates (since corrected in more recent plates), and (2) partial blockage in one of the two cooling plates, due to fabrication temperature non-uniformity. Further evaluation of these results is needed, but performances of both experimental components appear generally encouraging.

TASK V - FUEL PROCESSING SUPPORT

The intent of this task is to provide background data and information to support the design and construction of an optimized

SECTION II. - CONTINUED

50kW fuel processor under Task III. Most of the effort of this task was devoted to screening and longevity testing of catalysts for methanol/steam reforming. This task is now complete. The results were summarized in the Fifth Quarterly Report (February - April, 1982).

TASK VI - IMPROVED ELECTROCATALYSTS

Developmental electrocatalyst formulations are being prepared under Engelhard sponsorship. These are provided to the main program, and results are reported under Task IV.

SECTION III. - CURRENT PROBLEMS

NONE.

SECTION IV. - WORK PLANNED

TASK I

- 5kW integrated methanol system testing to continue.

TASK II

- ADL to conclude economic analysis and begin market projections.

TASK III

- Construction of 50kW methanol reformer sub-system to continue.

TASK IV

- Testing of graphite plates and non-metallic cooling plates in sub-scale stack to be evaluated.

TASK V

- Completed.

SECTION V. FINANCIAL MANAGEMENT ANALYSIS

TASK I - 5kW POWER SYSTEM DEVELOPMENT

Labor effort continued on stack and system testing during October. Expenditures were minor, but the total cost for this task now exceeds the budget figure by about $1000.

TASK II - ON-SITE SYSTEM APPLICATION ANALYSIS

Expenditures continued on this task in October as a result of subcontract activities at ADL.

TASK III - ON-SITE SYSTEM DEVELOPMENT

1. Large Stack Development

Labor hours for this sub-task increased in October as activities in preparation for the 25kW stack intensified.

2. Large Fuel Processor Development

Cost and hours through October remain about 10% below plan to date.

3. System Analysis

Physical Sciences Inc. subcontract billing has been completed. Internal labor charges continued in October at a low level.

SECTION V. - CONTINUED

4. System Integration

Internal labor on this task increased substantially in October reflecting an increase in system integration activity.

TASK IV - STACK SUPPORT

Manpower expenditures for this task were at a high level again in October. Total expenditures are now near the budget projections.

TASK V - FUEL PROCESSING SUPPORT

Manpower requirements for methanol reforming catalyst evaluation have been completed. Total expenditures required were well below those projected.

TASK VI - IMPROVED ELECTROCATALYSTS

The development of advanced anode and cathode catalysts is proceeding under Engelhard sponsorship. Evaluation of these catalysts is accomplished under Task IV.

TASK VII - MANAGEMENT AND DOCUMENTATION

Expenditures in the management and documentation area are proceeding substantially according to plan.

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TABLE I

SELECTION CRITERIA FOR OS/IES DEMONSTRATION SITES

(in declining order of importance)

(Source: Arthur D. Little, Inc.)

1. Appropriateness of Load Profile

   - High hot water to electricity
   - High electricity, hot water per square foot

2. Attractive Electric Rate Structure

   - High electric rate
   - High buy-back rate

3. Acceptable Institutional Factors

   - Traditional use of HVAC engineers
   - Long-term orientation
   - Low tax status
   - Presence of competent operating personnel
   - Tradition of accommodating innovation

4. Proximity to Engelhard, to Allow Greater Control and Monitoring

5. High Total Market Potential for Building Type

6. High Projected Rate of Return for Specific Site.

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TABLE II

OPTIMUM BUILDING CONFIGURATIONS AND RETURNS ON INVESTMENT (PRELIMINARY DATA)

(Consolidated Edison Rates)

Building	Floor Area M^2 (ft^2)	No. of 50kW Stack Modules	Thermal Storage 10^3 liters (10^3 gal)	Chiller kW		Boiler kW (MMBtu)	IRR (%)
				Absorption	Centrifugal (tons)		
Retail Store	10,420 (112,163)	1	0		1,108 (315)	293 (1.0)	20.49
Apartment Complex	7,616 (81,984)	10	37.8 (10)	281		175 (0.6)	28.06
Hospital	18,292 (196,900)	1	189.3 (50)		1,090 (310)	2,314 (7.9)	33.53
Office Building (Washington, DC)	1,826 (19,653)	1	0		651 (185)	733 (2.5)	23.07
Office Building (Chicago)	1,926 (19,653)	1	0		633 (180)	938 (3.2)	22.34
Office Building (Houston)	1,826) (19,653)	1	0		721 (205)	440 (1.5)	18.29

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TABLE III

BUILDING MAXIMUM IRR SUMMARY

(Preliminary Data - Keyed to Table II)

Building	Con Edison	Georgia	Houston	Commonwealth
Retail Store	20.49	0	0	0
Garden Apartment	28.06	0	0	0
Hospital (Taxed)	33.53	17.34	0	0
Office (Washington, DC)	23.07	0	0	0
Office (Chicago, IL)	22.34	0	0	0
Office (Houston, TX)	18.29	0	0	0

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TABLE IV

INCREMENTAL RATES OF RETURN FOR
OS/IES CON EDISON ELECTRIC RATES

(Revised Data)

Building	Base Case Number of 50kW Modules	Analysis Case Number of 50kW Modules	IRR[1] (%)
Retail Store	0	1	19.85
	1	19	17.80
	19	20	10.81
Apartment	0	11	27.46
	11	12	11.36
Hospital	0	1	28.63
	1	2	27.95
	2	23	25.34
	23	30	25.30
	30	45	25.30
	45	63	25.25
Office - Houston	0	1	17.85
	1	13	14.78

[1]Assumes 45% tax rate

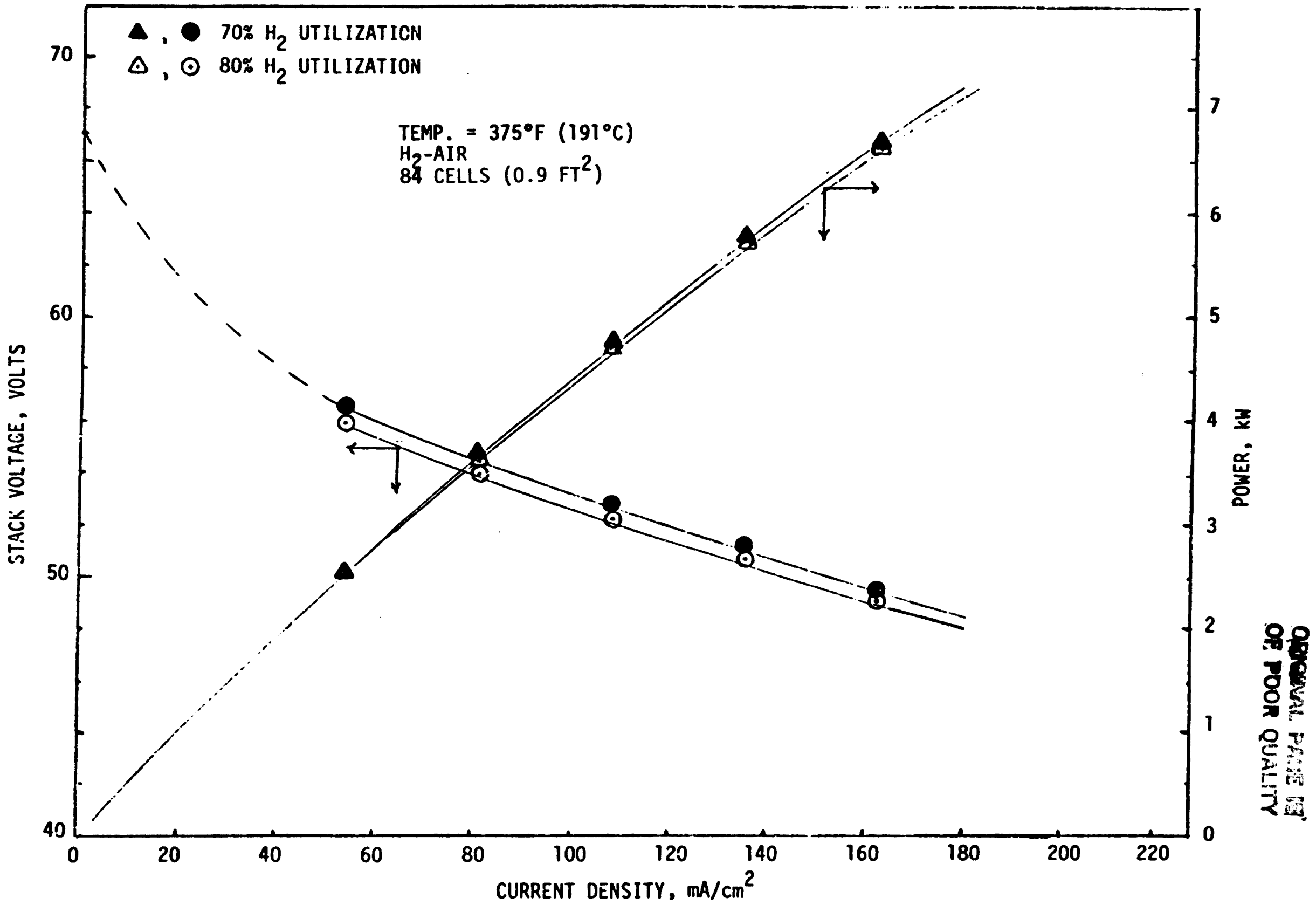

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FIGURE 1 PERFORMANCE CURVES FOR REBUILT 5-kW STACK

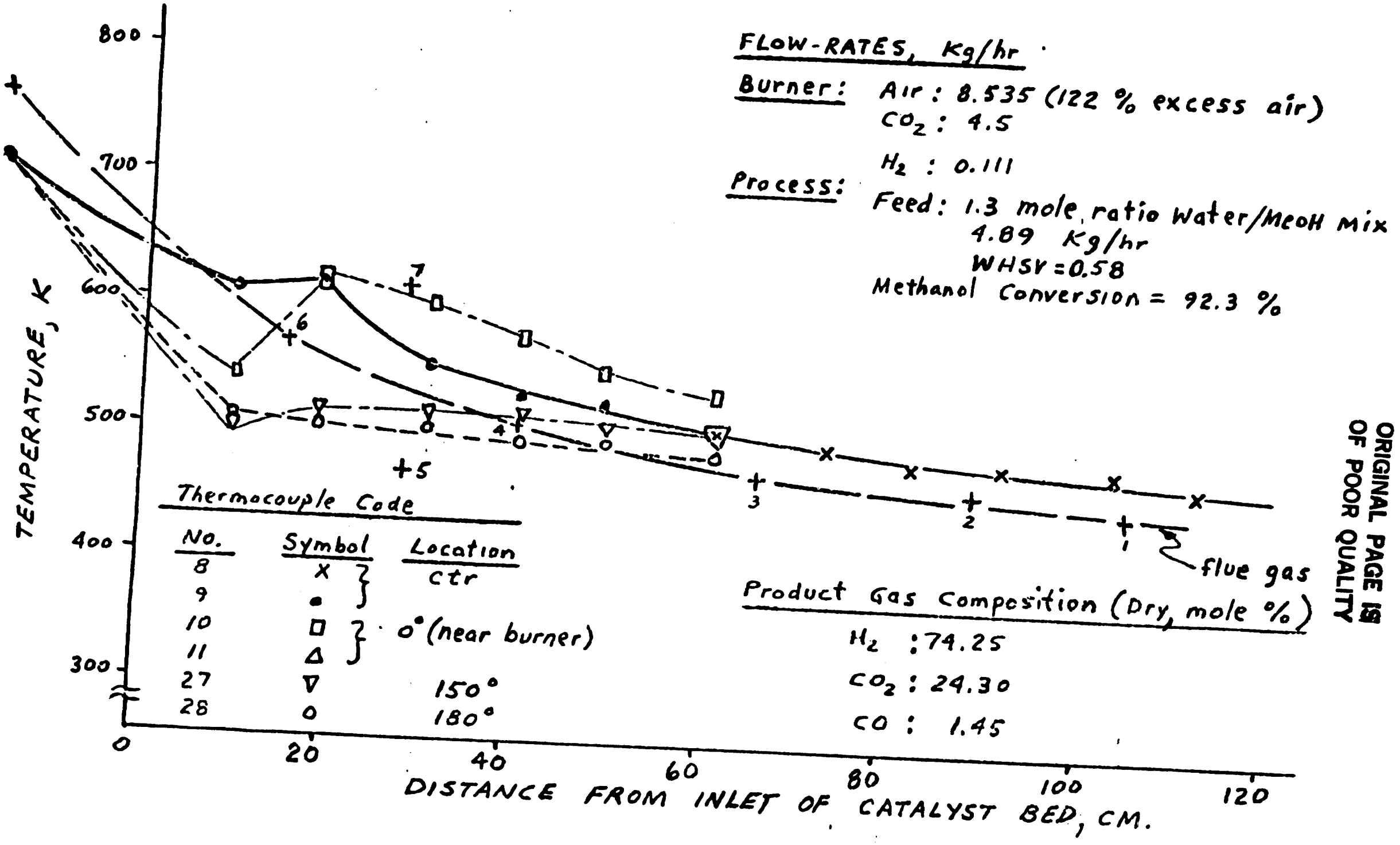

FIGURE 2. METHANOL-STEAM REFORMING.

RUN NO. 11779-1
132 % of Design CH_3OH-H_2O Feed Rate
700 K Process Gas Inlet Temp.
122 % Excess Air to Burner.

J.A. Whelan 8-4-82

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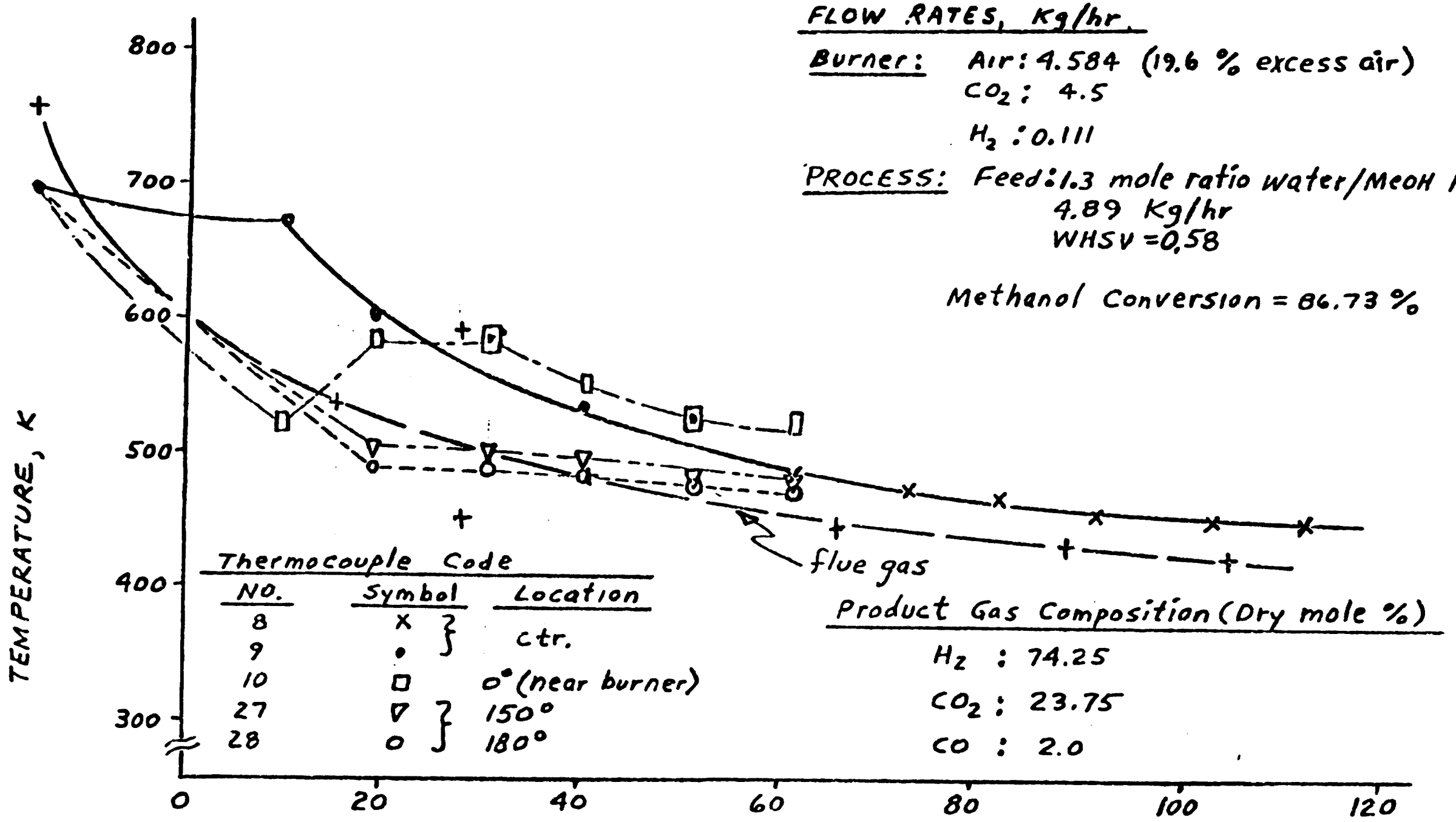

FLOW RATES, Kg/hr.

Burner: Air: 4.584 (19.6 % excess air)
CO_2 : 4.5
H_2 : 0.111

PROCESS: Feed: 1.3 mole ratio water/MeOH Mix
4.89 Kg/hr
WHSV = 0.58

Methanol Conversion = 86.73 %

Product Gas Composition (Dry mole %)

H_2 : 74.25
CO_2 : 23.75
CO : 2.0

FIGURE 3. METHANOL-STEAM REFORMING.

RUN NO. 11762-40
132 % of Design CH_3OH-H_2O Feed Rate
700 K Process Gas Inlet Temp.
19.6 % Excess Air to Burner. J.A. Whelan 8-4-82

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